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Investigation on the combustion characteristics and particulate emissions from a diesel engine fueled with diesel-biodiesel-ethanol blends

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ABSTRACT

This study investigated the influence on the combustion characteristics and particulate emissions of a diesel engine fueled with DBE (diesel-biodiesel-ethanol) blended fuels. The effects on in-cylinder pressure, heat release rate, combustion duration, diffusion fuel mass, BSPM (brake specific particulate mass) and BSPN (brake specific number concentrations) when diesel-biodiesel is blended with 0%, 5%, 10% and 20% ethanol were tested in a 4-cylinder naturally-aspirated direct-injection diesel engine at a steady state speed of 1800 rev/min under five engine loads. Overall, compared with ULSD (ultra-low-sulfur diesel), DBE blends can effectively reduce BSPM, BSPN and maintain a good trade-off relationship among PM-PN-NO_X. Compared with biodiesel, the blended fuels perform better in suppressing BSPN, leading to a reduction in the number of ultrafine and nano-particles.

1. Introduction

Diesel engines are widely used in commercial applications. However, there is serious concern on their emissions, in particular the nitrogen oxides (NO_x), PM (particulate matters) and carbon dioxide (CO_2). In the last few decades, the significant global warming problems caused by CO_2 have been magnified by the continued and increasing use of petroleum in diesel engines. Reducing CO_2 emission has become an explicit goal of policy measures to support the use of biofuels. For example, European Union mandates 10% share for biofuels in the EU (European Union) total energy mix by 2020 [1] and United States sets a total of 36 billion-gallon target for biofuel production by 2022 [2]. Therefore, alternative renewable biofuels have been investigated to partly or completely replace diesel fuel to overcome the emission problems. Of the alternative biofuels, the most widely investigated include biodiesel and ethanol [3–5]. These two fuels have clear emission advantages over diesel fuel. However, some studies have raised the concern of "food versus fuel" arising from plant-based biodiesel and ethanol, which might be the main hurdle for commercialization [6]. In fact, the economic consequences of these biofuel expansions are mixed and there are still some issues that will influence the actual impacts on food costs that have not been accounted for [7]. To counter the "food, energy and environment trilemma", the development of these biofuels from non-food sources (i.e. biodiesel from waste cooking oil, ethanol from cellulosic non-food crops, etc) can show great promise in reducing food commodities being utilized for biofuel production [8].

Different biodiesels, including those produced from low-cost waste cooking oil, have been investigated for application to diesel engines directly without the need to modify the engine. The direct use of biodiesel can reduce HC (hydrocarbon), CO (carbon monoxide) and particle-mass emissions but with technical constraints for increase in fuel consumption, particle-number and NOx emissions. Investigations have then been carried out for diesel-biodiesel blended fuels for improving the subject technical constraints brought from biodiesel [9–11]. More recently, Rakopoulos et al. [12] investigated influence of various common biofuels (including vegetable oil, biodiesel, ethanol, n-butanol, diethyl ether), blended with diesel, on the combustion and emissions of a diesel engine, with emphasize on the effect of fuel-bound oxygen contents. Ethanol is considered as a promising fuel oxygenate because its high heat of evaporation favors NOx reduction while its high oxygen content favors PM reduction. However, ethanol and diesel can only be mixed with the assistance of fuel stabilizer [10]. Biodiesel molecule is known to have a polar end with affinity for ethanol, which is also polar in nature, thus, biodiesel can be used as an effective stabilizer in preventing the separation of

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Nomenclature

BMEP	brake mean effective pressure
CO_2	carbon dioxide
CO	carbon monoxide
DBE	diesel-biodiesel-ethanol blends
HC	hydrocarbons
NO_X	nitrogen oxides
PM	particulate matters
PN	particle number concentrations
ULSD	ultra-low-sulfur diesel
SOC	start of combustion
EOC	end of combustion
TDC	top dead center
Øp	premixed combustion phase
Ød	diffusion combustion phase

ethanol from diesel fuel [13]. Investigations have therefore been carried out to investigate the combined use of biodiesel and ethanol in diesel fuel. As such, DBE (diesel-biodiesel-ethanol) blended fuel has been studied in recent years so that the disadvantages of either diesel-biodiesel or diesel-ethanol blended fuels can be overcome [13–17]. For example lubricity and cetane number of diesel fuel will be degraded by ethanol due to its lower density and viscosity while biodiesel has good lubricity and high cetane number which could enhance the lubricity and cetane number of diesel-ethanol blends [14,18]. Investigations on DBE for diesel engines can be traced back to as early as 1995. Ali et al. [19,20] investigated the effect of DBE on engine performance and gaseous emissions. Shi et al. [21] used DBE blends with 5% ethanol, 20% methyl soyate and 75% diesel fuel by volume. The DBE showed a significant reduction in PM emission but 2–14% increase in NO_x emission. Certain carbonyls were also measured and found to increase slightly with DBE. Guarieiro et al. [22] found that the combustion efficiency could be enhanced by the addition of ethanol and three kinds of biodiesels (methyl soybean ester, methyl castor ester and methyl residual oil ester) in diesel fuel which resulted in more complete combustion and reduced NOx emission in the ranges of 6.9%–7.5% at 1800 rev/min and 4%–85% at 2000 rev/min. 18 carbonyl compounds were also measured and the emission rate of total carbonyl compounds increased with DBE. Jha et al. [23] studied emissions from DBE blends with 5% diesel-70% biodiesel-25% ethanol, 10% diesel-70% biodiesel-20% ethanol and 15% diesel-70% biodiesel-15% ethanol on both new and used diesel engines. They found that DBE blends significantly reduce NOx emission in new engines with increase of ethanol fraction whereas the old engine showed increase in NOx emission. Moreover, CO emissions increased with increasing ethanol proportion in the blends in both new and old engines. Cheenkachorn et al. [24] studied the fuel properties and tested DBE blends with 84% diesel, 0.25% hydrous ethanol, 4.75% anhydrous ethanol and 11% biodiesel on a light-duty truck on a chassis dynamometer simulating the Bangkok driving cycle and found reduced PM and CO emissions as compared to diesel fuel. Hulwan et al. [25] reported that DBE blends with 20–40% ethanol attained significant smoke reduction and increased NO_X emission at high engine loads as compared with diesel fuel. They also measured the in-cylinder pressure and evaluated the heat release rate. Pidol et al. [26] tested three diesel-FAME-ethanol blends on a multi-cylinder DI (Direct Injection) diesel engine and a single cylinder diesel engine and found that smoke level was lower than using diesel fuel due to the presence of oxygen, decrease of soot precursors concentration and higher volatility of the blended fuel. Yilmaz et al. [15,17] have also investigated DBE on diesel engines with focus on the influence of ethanol concentration on engine performance and regulated gaseous emissions, with up to 25% ethanol in the fuel. Qi et al. [11,27] investigated the combustion and emissions characteristics of a diesel engine using different fuels including a DBE with 5% ethanol. The influence on in-cylinder pressure, rate of pressure rise and heat release rate were compared among the different fuels. Fang et al. [28] investigated effects of DBE on the combustion characteristics and emissions of a diesel engine in premixed low temperature combustion, however, particulate emission was not investigated. More recently, Lee et al. [29] investigated DBE with water and Chang et al. [30] investigated acetone-butanol-ethanol as blending additive in a diesel engine fueled with biodiesel and diesel for reducing NOx emissions. Previous works on DBE blends mainly focused either on reducing CO, HC, NO_X or PM mass concentration. However, due to the strong links between particle number concentrations and health effects, it is more important to have in-depth study on the particulate number-size distributions for better understanding about the potential use of DBE blends. Kim and Choi [31] investigated the effect of biodiesel and bioethanol blended diesel fuel on nanoparticle and exhaust emissions from a common-rail direct injection diesel engine. Their study involved a DBE blend with 80% diesel-15% biodiesel-5% ethanol and they found that the DBE blend was much more effective in reducing particle number and particle mass when compared with B20 (80% diesel-20% biodiesel). Muralidharan et al. [18] also investigated DBE blends with 5% ethanol. They concluded that the particle size and number reduced with DBE blends. Armas et al. [13] investigated the influence of a DBE blend with 10% ethanol on the emission of a bus. They found a slight increase in nuclei mode particles despite a reduction in total number concentration. In these studies, the influence of different concentrations of ethanol in the DBE has not been investigated.

The above review shows that very few studies on DBE blends are related to the combustion characteristics and particle number concentrations. A significant number of particles emitted by diesel engines are in the nano-size range with diameter less than 50 nm while most of the mass-based PM is in the accumulation mode with diameter in the range of 50 nm–1000 nm [17]. The smaller the emitted particles, the more harmful they are because smaller particles can more easily infiltrate into the respiratory organs of human body. On the other hand, ethanol has very low cetane number and hence the ethanol content in DBE would affect ignition delay and hence subsequent heat release characteristics as well as the emissions. Ignition delay will affect the start of combustion, combustion duration and diffusion burning thereby affecting the PM emissions. The correlation between these combustion characteristic parameters and the particulate emissions for DBE blends, over a range of ethanol content, has not been studied. The aim of this study is to fill in this knowledge gap. It aims at investigating the influence of DBE on the combustion characteristics and particulate emissions, both by mass and by number, of a diesel engine. The DBE used has ethanol content ranging at 0%, 5%, 10% and 20% while the biodiesel used is manufactured from waste cooking oil.

In this investigation, effects of DBE blends on HC and CO emissions have also been measured and published in Tse et al. [32]. The results are not repeated in this paper because they are mostly in-line with those published in the literatures.

2. Experimental investigation

The fuels used in this study include ULSD (ultralow-sulfur diesel fuel), biodiesel and ethanol. The major properties of them are shown in Table 1. Euro V diesel fuel contains less than 10 ppm sulfur by weight. The biodiesel, produced by Dynamic Progress from

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